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PHYSICS LETTERS B

Physics Letters B 567 (2003) 227–234

www.elsevier.com/locate/npe

Primordial nucleosynthesis in light of WMAP

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Received 4 March 2003; received in revised form 4 June 2003; accepted 17 June 2003

Editor: W. Haxton

Abstract

Big bang nucleosynthesis has long provided the primary determination of the cosmic baryon density $\Omega_B h^2$, or equivalently the baryon-to-photon ratio, η . Recently, data on CMB anisotropies have become increasingly sensitive to η . The comparison of these two independent measures provides a key test for big bang cosmology. The first release of results from the Wilkinson Microwave Anisotropy Probe (WMAP) marks a milestone in this test. With the precision of WMAP, the CMB now offers a significantly stronger constraint on η . We discuss the current state of BBN theory and light element observations (including their possible lingering systematic errors). The resulting BBN baryon density prediction is in overall agreement with the WMAP prediction, an important and non-trivial confirmation of hot big bang cosmology. Going beyond this, the powerful CMB baryometer can be used as an input to BBN and one can accurately predict the primordial light element abundances. By comparing these with observations one can obtain new insight into post-BBN nucleosynthesis processes and associated astrophysics. Finally, one can test the possibility of nonstandard physics at the time of BBN, now with all light elements available as probes. Indeed, with the WMAP precision η , deuterium is already beginning to rival ^4He 's sensitivity to nonstandard physics, and additional D/H measurements can improve this further.

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1. Introduction

The primordial light element abundances are predicted accurately and robustly by the theory of Big Bang Nucleosynthesis (BBN) [1,2], describing the first 3 minutes of the hot early universe. This hot big bang model also predicts a relic photon background, produced when nuclei recombined to form neutral atoms some 400 000 years later. The Cosmic Microwave Background (CMB), and its anisotropies

carry key information about the content of the universe and early structure growth. In particular, both BBN and the CMB are sensitive to the baryon content in the universe and because they are governed by different physics, BBN and the CMB can be used as independent measures of the cosmic baryon density, $\rho_B \propto \Omega_B h^2$, or equivalently the baryon-to-photon ratio, η .

The comparison of the baryon density predictions from BBN and the CMB is a fundamental test of big bang cosmology [3], and its underlying assumptions, which include: a nearly homogeneous, isotropic universe, with gravity described by General Relativity and microphysics described by the Standard Model of

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particle physics.¹ In the standard model, we fix the number of neutrino flavors to three, and we allow this number to vary in order to test models beyond the standard model. Furthermore, standard BBN relies on a network of nuclear reactions which are taken from low energy cross section measurements. Any deviation from concordance points to either unknown systematics or the need for new physics. Up till now, there has been tentative agreement between the baryon density predictions from BBN and the CMB, barring the internal tension between BBN derived limits from deuterium and ⁷Li observations. With the first data release from the Wilkinson Microwave Anisotropy Probe (WMAP), the anisotropies in the CMB have been measured to unprecedented accuracy [4]. This new precision allows for a CMB-based determination of the baryon density which is significantly tighter than current BBN analysis yields. One no longer needs to use BBN as a probe of the baryon density. Instead, the CMB baryon density can be used as an input for BBN, and the light element abundance observations can be used to test particle physics and nuclear astrophysics [5,6].

This Letter is organized as follows. In Section 2, we discuss the state of affairs of primordial nucleosynthesis before WMAP. We then explain how the post-WMAP CMB compares with BBN in Section 3, and go on to constrain astrophysics (Section 3.1) and particle physics (Section 3.2). We conclude with a discussion of our results and aspirations for the future.

2. The baryon density from BBN (pre-WMAP)

The baryon density (or the baryon-to-photon ratio, $\eta \equiv n_{10}/10^{10}$) is the sole parameter in the standard model of BBN. Prior to the recent measurements of the microwave background power spectrum, the best available method for determining the baryon density of Universe was the concordance of the BBN predictions and the observations of the light element abundances of D, ³He, ⁴He, and ⁷Li. A high-confidence upper limit to the baryon density has long been avail-

able [7] from observations of local D/H abundance determinations (giving roughly $\eta_{10} < 9.0$), but a reliable lower bound to η , much less a precise value, has been more elusive to obtain. Lower bounds to η have been derived (1) on the basis of D + ³He observations (using arguments based on chemical evolution) [8], (2) from early reports (now understood to be erroneous) of high D/H in quasar absorption systems, and (3) in likelihood analyses using the combined ⁴He, ⁷Li and D/H observations [9–12]. The last method gives a 95% CL range of $5.1 < \eta_{10} < 6.7$ with a most likely value of $\eta_{10} = 5.7$ corresponding to $\Omega_B h^2 = 0.021$.

Observations of each of the light elements D, ⁴He, and ⁷Li can be used to determine the value of η . Despite great progress theoretically and observationally [13], ³He is not as yet a strong baryometer [14] (but see below, Section 3.1). Each of the light elements is observed in vastly different astrophysical environments: D/H in high-redshift QSO absorption line systems; ⁴He in extragalactic H II regions; and ⁷Li in low metallicity halo stars. Confidence in any such determination however, relies on the concordance of the three light isotopes. One concern regarding the likelihood method is, in fact, the relatively poor agreement between ⁴He and ⁷Li on the one hand and D on the other. The former two taken alone indicate that the most likely value for η_{10} is 2.4, while D/H alone implies a best value of 6.1. This discrepancy may point to new physics, but could well be due to underestimated systematic errors in the observations. More weight has been given to the D/H determinations because of their excellent agreement with the (pre-WMAP) CMB experiments.

3. The baryon density from the CMB and beyond

The power spectrum of CMB temperature anisotropies contains a wealth of information about a host of cosmological parameters, including η [15]. In the past few years, pioneering balloon and ground-based observations have made the first observations at multipoles $l \gtrsim 200$, where the sensitivity to η lies, and constraints on η reached near the sensitivity of BBN [16]. Already, these experiments had revealed the first two acoustic peaks in the angular power spectrum, and hints of a third. The improvement offered by WMAP [4] was thus a quantitative one: with its all-sky cover-

¹ Other, somewhat more technical assumptions are that no comoving entropy change occurs between BBN and the CMB, and that the neutrino chemical potentials are small, i.e., that the cosmic lepton number $n_l/n_\gamma \ll 1$.

age, high signal-to-noise, and broad angular coverage, WMAP offers a major advance in our understanding of the CMB and allows the CMB-based inference of the baryon-to-photon ratio to reach a new level of precision.

The CMB-based baryon density must be extracted from the observed angular power spectrum of temperature anisotropies. This process requires several assumptions. In addition to adopting the basic hot big bang framework, outlined above, some more specific assumptions are required. These are: (1) gaussian random fluctuations; (2) flat priors over the adopted range of parameters; (3) an adiabatic primordial power spectrum of density fluctuation described by a single, constant spectral index, or by an index with a constant logarithmic slope versus k . The baryon density is then determined simultaneously with several other key cosmological parameters which include: the total matter density, the Hubble parameter, spectral index and optical depth. In addition, other data sets can be adopted to further constrain the cosmological parameters (including Ω_B). The WMAP best fit result is for a varying spectral index, and is [4] $\Omega_B h^2 = 0.0224 \pm 0.0009$, or

$$\eta_{10, \text{CMB}} = 6.14 \pm 0.25 \quad (1)$$

a precision of 4%! This estimate is the best-fit WMAP value, which is sensitive mostly to WMAP alone (primarily the first and second acoustic peaks) but does include CBI [17] and ACBAR [18] data on smaller angular scales, and Lyman α forest data (and 2dF redshift survey data [19]) on large angular scales.

The various data sets, and assumptions regarding the spectral index, all influence the “best fit” WMAP baryon density. For WMAP data alone, the baryon density is $\Omega_B h^2 = 0.024 \pm 0.001$ for a constant spectral index in a Λ CDM cosmology; this value is about 1.6σ above the best fit. The CBI and ACBAR data serve to decrease $\Omega_B h^2$ by about 0.001 units, and the Lyman α data make a smaller shift, but in opposite directions depending on the constant or running nature of the spectral index. For the rest of the Letter, unless stated otherwise we will adopt the best-fit value. Clearly, other reasonable assumptions will lead to somewhat different $\Omega_B h^2$, and moreover the result (or at least the error budget) will certainly change as additional WMAP data becomes available. To illustrate this point, we will use the WMAP-only results at the end of Section 3.1 to illustrate the

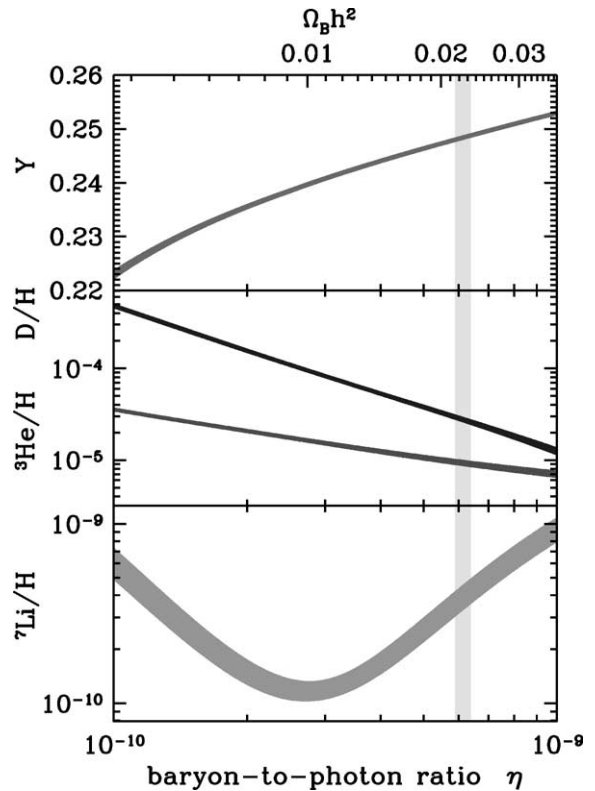


Fig. 1. Abundance predictions for standard BBN [12]; the width of the curves give the $1 - \sigma$ error range. The WMAP η range (Eq. (1)) is shown in the vertical band.

impact of other assumptions. Despite these issues, our point in this Letter is to illustrate the impact of the current WMAP results on BBN, and to highlight new opportunities and challenges for BBN.

Fig. 1 shows the light element abundance predictions of standard BBN taken from the recent analysis of [12], as well as the η range determined by the CMB in Eq. (1). This range in η overlaps with the BBN predicted range (particularly for the range obtained using D/H) indicating consistency between the BBN and CMB determinations of η . These two techniques involve very different physics, at different epochs, and rely on observations with completely different systematics. Thus, these are independent measurements of the cosmic baryon content, and their agreement signals that the standard hot big bang cosmology has passed a crucial test in impressive fashion.

However, we recall that the BBN η range based on ${}^7\text{Li}$ and ${}^4\text{He}$ are in poor agreement with D .

This internal tension to BBN also guarantees that at least *one* element must disagree with the CMB. However, now the CMB can act as a “tiebreaker”, strongly suggesting that the D/H measurements are accurate, while both the ^4He and ^7Li abundances are systematically small. This is just one example of the new kinds of analysis now made possible by using the high-precision CMB η as an *input* to BBN [5]. We now turn to a survey of other such possibilities.

3.1. Using BBN and the CMB to probe astrophysics

In light of the WMAP determination of η_{10} (Eq. (1)), we now have a very precise prediction for the primordial abundances of all of the light elements. Our new BBN predictions for each of the light element abundances are shown in Fig. 2 by the dark shaded distributions. When these are compared to the observational abundances (shown as the lighter shaded distributions) the most conservative interpretation of any discrepancy is a systematic effect in observational determination. These differences offer a unique window into the astrophysical processes which are related to the abundance measurement in both primitive and evolved systems. We describe each of these briefly in turn.

The primordial D/H abundance is predicted to be:

$$(D/H)_p = 2.751^{+0.24}_{-0.19} \times 10^{-5} \quad (2)$$

a precision of about 8%.² For comparison, the uncertainty in the BBN prediction alone at this η is about 4%, so that the CMB error in η dominates, but as this improves the BBN error will become significant unless it is reduced. We note that the predicted value in Eq. (2) is slightly higher than the value of $D/H = 2.62^{+0.18}_{-0.20} \times 10^{-5}$ quoted in [4], this is largely due to our use of the most recent nuclear rates as determined by the NACRE Collaboration [24]; at higher values of eta, this leads to 5–10% more D/H than older rates [5]. As one can see from Fig. 2a, this is in excellent agreement with the average of the 5 best determined quasar absorption system abundances [20–23] which give $D/H = (2.78 \pm 0.29) \times 10^{-5}$. It appears that deuterium in the two systems with multiple-line measure-

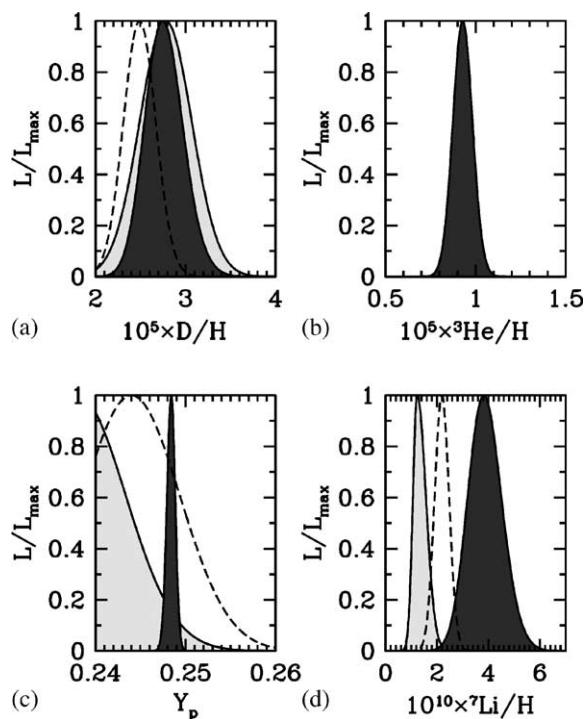


Fig. 2. Primordial light element abundances as predicted by BBN and WMAP (dark shaded regions). Different observational assessments of primordial abundances are plotted as follows: (a) the light shaded region shows $D/H = (2.78 \pm 0.29) \times 10^{-5}$ [20–23], while the dashed curve shows $D/H = (2.49 \pm 0.18) \times 10^{-5}$ [21, 22]; (b) no observations plotted; (c) the light shaded region shows $Y_p = 0.238 \pm 0.002 \pm 0.005$ [25], while the dashed curve shows $Y_p = 0.244 \pm 0.002 \pm 0.005$ [26]; (d) the light shaded region shows $^7\text{Li}/H = 1.23^{+0.34}_{-0.16} \times 10^{-10}$ [27], while the dashed curve shows $^7\text{Li}/H = (2.19 \pm 0.28) \times 10^{-10}$ [28].

ments [21,22], with $D/H = (2.49 \pm 0.18) \times 10^{-5}$, may be systematically low (as are the DLA systems in general [21–23]); however, it may be that the error budget is underestimated [22].

When taken in conjunction with local ISM determinations of D/H, we see that D/H has been destroyed by only a factor of $\lesssim 2$, which further implies that the galactic evolution in the disk of our Galaxy has been rather tame compared with the degree of cosmic evolution as evidenced by the cosmic star formation rate (see, e.g., [29]). In fact, we can quantify the fraction of local material that has passed through stars: adopting the recent FUSE Local Bubble value of $(D/H)_{\text{ISM}} = (1.52 \pm 0.08) \times 10^{-5}$ [30], we see that $D_{\text{ISM}}/D_p = 55^{+6}_{-4}\%$ of the Local Bubble material has

² Note here and throughout that the uncertainties quoted are at the 1σ or 68% central confidence limit, unless otherwise noted.

never passed through a star. The FUSE data strongly suggests that D/H varies outside of the Local Bubble, so that the D/D_p ratios measure the unprocessed fraction towards each line of sight sampled.

The ^3He abundance is predicted to be:

$$^3\text{He}/H = 9.28^{+0.55}_{-0.54} \times 10^{-6}. \quad (3)$$

Unfortunately, as has been argued repeatedly, it is very difficult to use local ^3He abundance measurements in conjunction with the BBN value. The primary reason is our uncertainty in the stellar and chemical evolution of this isotope over the history of our Galaxy. Nevertheless, some general statements can be made. For the most part, the average ^3He abundance seen in Galactic H II regions [13] is slightly higher than the above primordial value although the uncertainties are large. A few of the systems show abundances at or below this, while most lie above. Thus one may be tempted to conclude that, averaged over initial masses, stars are net producers of ^3He . On the other hand, if the H II regions with abundances apparently *below* the primordial level can be confirmed to be ^3He -poor, this would underscore the difficulty of using ^3He to do cosmology, but would at the same time offer important hints into low-mass stellar evolution as well as the chemical evolution of the Galaxy and its H II regions [14].

The ^4He abundance is predicted to be:

$$Y_p = 0.2484^{+0.0004}_{-0.0005}. \quad (4)$$

This value is considerably higher than any prior determination of the primordial ^4He abundance. Indeed it is higher than well over half of the over 70 low metallicity H II region determinations [25,26,31,32]. While it has been recognized that there are important systematic effects which have been underestimated [33], it was believed (or at least hoped) that not all of the H II regions suffered from these. Among the most probable cause for a serious underestimate of the ^4He abundance is underlying stellar absorption. Whether or not this effect can account for the serious discrepancy now uncovered remains to be seen. Note that the ‘observed’ distribution shown in Fig. 2c already includes an estimate of the likely systematic uncertainties.

The ^7Li abundance is predicted to be:

$$^7\text{Li}/H = 3.82^{+0.73}_{-0.60} \times 10^{-10}. \quad (5)$$

This value is in clear contradiction with most estimates of the primordial Li abundance. The question of systematic uncertainties is now a serious and pressing issue. A thorough discussion of possible systematic uncertainties was presented in [27]. The result of that analyses was a ^7Li abundance of $^7\text{Li}/H = 1.23^{+0.34}_{-0.16} \times 10^{-10}$ which is a factor of 3 below the WMAP value, and almost a factor of 2 below even when systematics are stretched to maximize the ^7Li abundance. Once again, the most conservative conclusion that one can reach is that the systematic uncertainties have been underestimated. One possible culprit in the case of ^7Li is the assumed set of stellar parameters needed to extract an atmospheric abundance. In particular, the abundance is very sensitive to the adopted surface temperature which itself is derived from other stellar observables. However, even a recent study [28] with temperatures based on $H\alpha$ lines (considered to give systematically high temperatures) yields $^7\text{Li}/H = (2.19 \pm 0.28) \times 10^{-10}$. Another often discussed possibility is the depletion of atmospheric ^7Li . This possibility faces the strong constraint that the observed lithium abundances show extremely little dispersion, making it unlikely that stellar processes which depend on the temperature, mass, and rotation velocity of the star all destroy ^7Li by the same amount. To be sure, uniform depletion factors of order 0.2 dex (a factor of 1.6) have been discussed [34]. It is clear that either (or both) the base-line abundances of ^7Li have been poorly derived or stellar depletion is far more important than previously thought. Of course, it is possible that if systematic errors can be ruled out, a persistent discrepancy in ^7Li could point to new physics.

We also note that the WMAP determination, Eq. (5), has important implications for Galactic cosmic-ray nucleosynthesis (GCRN). A non-negligible component of ^7Li is produced together with ^6Li by GCRN, predominantly from $\alpha + \alpha$ fusion [35]. Since this process is the only known source of ^6Li , and the abundance of ^6Li is determined as the ratio $^6\text{Li}/^7\text{Li}$ in the same metal poor stars, the enhanced primordial ^7Li abundance also implies more GCRN than previously thought. This in turn has important implications for cosmic rays in the proto-Galaxy.

As noted in Section 3, the baryon density derived from WMAP depends on the assumptions—choices of priors and non-WMAP data—which enter into the analysis. Among the suite of models presented by

WMAP, the variations in $\Omega_B h^2$ span a range of approximately 2σ . Thus, it is of interest to see the impact of other choices. As noted above, the baryon density we have adopted (Eq. (1)) comes from the WMAP “best-fit” model, which includes other data sets which have small but statistically significant effects on the inferred baryon density. We thus use the WMAP-only data results to illustrate the effect of the other data sets on the results.

The WMAP-only baryon density results [4] for a constant primordial spectral index gives $\Omega_B = 0.024 \pm 0.001$, or $\eta_{10} = 6.58 \pm 0.27$. Using these values and BBN theory we find $D/H = 2.47^{+0.22}_{-0.18} \times 10^{-5}$, ${}^3\text{He}/H = 8.89^{+0.55}_{-0.53} \times 10^{-6}$, $Y_p = 0.2491^{+0.0004}_{-0.0005}$, and ${}^7\text{Li}/H = 4.39^{+0.83}_{-0.69} \times 10^{-10}$. We see that the lower D/H value is still in good agreement with the world average, and actually in better agreement with the two best systems. Both ${}^4\text{He}$ and ${}^7\text{Li}$ are pushed somewhat further from the observed levels we have adopted, further pointing to systematic errors (or possibly new physics). Thus, while the quantitative differences are significant, the qualitative conclusions of this section remain the same.

3.2. Using BBN and the CMB to probe particle physics

With the goal of maintaining concordance, we examine how sharply we can deviate from the standard model. Often the effect of new physics can be parameterized in terms of additional relativistic degrees of freedom, usually expressed in terms of the effective number of neutrino species $N_{\nu,\text{eff}}$, with standard BBN having $N_{\nu,\text{eff}} = 3$. Traditionally, D or ${}^7\text{Li}$ observations were used to fix the baryon density and the ${}^4\text{He}$ mass fraction, was used to fix $N_{\nu,\text{eff}}$. These limits are thoroughly described elsewhere [2,11,36]. Moreover, as we have noted, the observed ${}^4\text{He}$ appears lower than the WMAP + BBN value. This discrepancy likely is due to systematic errors (but could point to new physics). Until this situation is better understood, caution is in order. Fortunately, in the post-WMAP era, we can now use the CMB-determined baryon density (Eq. (1)), to remove it as a free parameter from BBN theory and use any or all abundance observations to constrain $N_{\nu,\text{eff}}$ [5]. In particular, we have computed the likelihood distributions for $N_{\nu,\text{eff}}$ using η_{CMB} from

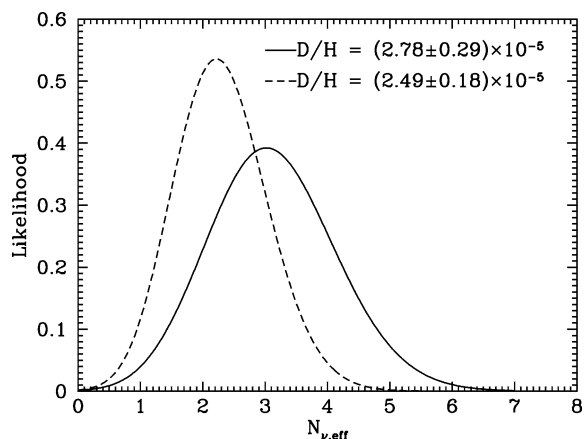


Fig. 3. Likelihoods for $N_{\nu,\text{eff}}$ as predicted by the WMAP η (Eq. (1)) and light element observations as in Fig. 2.

WMAP and different observations of the primordial D abundances; the results appear in Fig. 3.³

Unlike ${}^4\text{He}$, deuterium does not appear to suffer from large systematics. It is simply limited by the low number statistics due to the difficulty of finding high-redshift systems well-suited for accurate D/H determinations. Given that D predictions from WMAP agree quite well with observations, we can now use D to place an interesting limit on $N_{\nu,\text{eff}}$. D is not as sensitive to $N_{\nu,\text{eff}}$ as ${}^4\text{He}$ is, but nonetheless it does have a significant dependence. The relative error in the observed abundance of D/H ranges from 7–10%, depending on what systems are chosen for averaging. If the five most reliable systems are chosen, the peak of the $N_{\nu,\text{eff}}$ likelihood distribution lies at $N_{\nu,\text{eff}} \approx 3.0$, with a width of $\Delta N_{\nu,\text{eff}} \approx 1.0$ as seen in Fig. 3. However, if we limit our sample to the two D systems that have had multiple absorption features observed, then the peak shifts to $N_{\nu,\text{eff}} \approx 2.2$, with a width of $\Delta N_{\nu,\text{eff}} \approx 0.7$. Given the low number of observations, it is difficult to qualify these results. The differences could be statistical in nature, or could be hinting at some underlying systematic affecting these systems. Adopting the five system D average, $D/H = (2.78 \pm 0.29) \times 10^{-5}$, we get the following constraints on

³ Note that we have neglected the CMB’s own sensitivity to $N_{\nu,\text{eff}}$; since the CMB values for η and $N_{\nu,\text{eff}}$ are essentially independent [6,38,39], this does not bias our results, but means that ours is a more conservative limit.

$N_{\nu,\text{eff}}$:

$$\begin{aligned}\hat{N}_{\nu,\text{eff}} &= 3.02, \\ 2.10 < N_{\nu,\text{eff}} < 4.14 &\quad (68\% \text{ CCL}), \\ 1.26 < N_{\nu,\text{eff}} < 5.22 &\quad (95\% \text{ CCL}),\end{aligned}\tag{6}$$

where CCL is central confidence limit. Using a standard model prior assuming $N_{\nu,\text{eff}} \geq 3.0$ [37], the corresponding 95% CL upper limits are: $N_{\nu,\text{eff}} < 5.19$ for $D/H = 2.78 \times 10^{-5}$; $N_{\nu,\text{eff}} < 4.20$ for $D/H = 2.49 \times 10^{-5}$. For comparison, we also quote the corresponding limits based on ${}^4\text{He}$: $N_{\nu,\text{eff}} < 3.40$ for $Y_p = 0.238$; $N_{\nu,\text{eff}} < 3.64$ for $Y_p = 0.244$ also assuming the prior of $N_{\nu,\text{eff}} > 3.0$. Also for comparison, we note that the CMB itself also constrains $N_{\nu,\text{eff}}$ [6,38,39]. From the WMAP data alone, $N_{\nu,\text{eff}} < 6$ (95% CL) [39]. Note that it is conceivable that an evolving nonstandard component could lead to different $N_{\nu,\text{eff}}$ at the BBN and CMB epochs; as the data improve, this could be tested.

The new power of D to probe early universe physics will grow with the increasing precision in η_{CMB} and particularly with increasing accuracy in observed D/H. A 3% measurement in D will allow it to become the dominant constraint on $N_{\nu,\text{eff}}$ [5].

4. Discussion and conclusions

Primordial nucleosynthesis has entered a new era. With the precision observations of WMAP, the CMB has become the premier cosmic baryometer. The independent BBN and CMB predictions for η are in good agreement (particularly when D is used in BBN), indicating that cosmology has passed a fundamental test. Moreover, this agreement allows us to use BBN in a new way, as the CMB removes η as a free parameter. One can then adopt the standard BBN predictions, and use η_{CMB} to infer primordial abundances; by comparing these to light element abundances in different settings, one gains new insight into the astrophysics of stars, H II regions, cosmic rays, and chemical evolution, to name a few examples. Alternately, WMAP transforms BBN into a sharper probe of new physics in the early universe; with η_{CMB} fixed, *all* of the light elements constrain non-standard nucleosynthesis, with $N_{\nu,\text{eff}}$ being one example.

As BBN assumes a new role, much work remains to be done. To leverage the power of the WMAP

precision requires the highest possible precision in light element observations. Further improvements in the primordial D abundance can open the door to D as a powerful probe of early universe physics. Improved ${}^3\text{He}$ observations can offer new insight into stellar and chemical evolution. And perhaps most pressing, the WMAP prediction for primordial ${}^4\text{He}$ and particularly ${}^7\text{Li}$ are higher than the current observed abundances; it remains to be resolved what systematic effects (or new physics!) has led to this discrepancy.

WMAP also demands improvements in BBN theory. While the basic calculation is sound, accuracy of the WMAP light element predictions (Fig. 2) is or soon will be limited by the errors in BBN theory. These in turn arise from uncertainty in nuclear reaction cross sections [12,40]. In particular, the ${}^7\text{Li}$ prediction is completely dominated by the nuclear errors, especially that in the ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ reaction. The error in ${}^3\text{He}$ is also due to BBN uncertainties, in this case the $d(p, \gamma){}^3\text{He}$ and ${}^3\text{He}(d, p){}^4\text{He}$ reactions dominate the uncertainty. About half of the uncertainty in the CMB + BBN prediction of D is due to BBN errors, where again $d(p, \gamma){}^3\text{He}$ is important, as well as $p(n, \gamma)d$ and $d(d, n){}^3\text{He}$. We encourage intensified efforts to obtain high-precision measurements of these reactions, and their uncertainties.

In closing, it is impressive that our now-exquisite understanding of the universe at $z \sim 1000$ also confirms our understanding of the universe at $z \sim 10^{10}$. This agreement lends great confidence in the soundness of the hot big bang cosmology, and impels our search deeper into the early universe.

Acknowledgements

We thank Benjamin Wandelt for helpful conversations, and Ken Nollett for useful discussions regarding the differences between our BBN predictions. The work of K.A.O. was partially supported by DOE grant DE-FG02-94ER-40823. The work of B.D.F. and R.H.C. was supported by the National Science Foundation under grant AST-0092939.

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